Fermi National Accelerator Laboratory

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Raising the Acceptance of the AP2-Line

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1.INTRODUCTION

The 120 GeV Main Ring proton beam collides with the target at the end of the AP-1 line and creates antiprotons and other secondary particles. The AP-2 line transfers the negative particles from the target to the Debuncher. To provide a bigger antiproton stack size in the Accumulator, both the Debuncher as well as the AP-2 line acceptance have to be raised. This is a proposal for the improvement of the AP-2 line acceptance. The first part of the memo presents an acceptance examination of the existing AP-2 line by computer simulation, while the second presents a short proposal for aperture corrections.

The computer program TURTLE (Trace Unlimited Rays Through Lumped Elements)(1) was used to trace antiprotons through the AP-2 line without taking into account other negative charged particles. Betatron functions were obtained from the output of the SYNCH computer program(2). The SYNCH program was also used to check the dispersion match between the AP-2 line and the Debuncher.

The rays were first defined at evenly populated ellipses in the x-x' and y-y' phase spaces. The ellipses were created either in the Debuncher or downstream of the target with the betatron functions from the design report and from the SYNCH, respectively. The rays were traced from the ellipses in two directions:

1. The reverse direction - from the ellipses defined in the Debuncher backward to the target.

2. Directly - from the locations downstream of the target to the Debuncher.

Second, the rays were traced with the TURTLE from the target through the AP-2 line using a "real" distribution of the antiprotons at the target without taking into account the decay of other particles created at the target. From the real distribution at the target, the 20π up to 30π mm mrad emittances (not normalized to momentum), were defined by the corresponding positions of the collimator slits.

2. TRACING FROM THE EVENLY POPULATED ELLIPSES

2.1 Tracing in the Reverse Direction

The antiprotons were traced from the center of the D5Q2 quadrupole in the Debuncher. The rays were traced in the opposite direction through the line from the debuncher to the target. The loss of rays along the AP-2 line occurred at the same locations for different beam sizes starting from an emittance of 20π mm-mrad (for existing conditions) up to an emittance of 30π mm-mrad.

The results obtained from the reverse tracing are summarized in Table 1. In table 1 the beam sizes were obtained from the histograms when all aperture limitations were excluded. The corresponding ray losses of the 20π mm mrad and 28π mm mrad emittance beams represent a ray loss at that location only when

TABLE 1

REVERSE TRACING - AVAILABLE APERTURE WITH RESPECT TO THE BEAM SIZES OF 20π and 28π mm mrad EMITTANCES

LOCATION	AVAILABLE APERT. (mm) HOR.	VER.	BEAM SIZE(mm) 20π mm mrad HOR.	VER.	BEAM LOSS %	BEAM SIZE(mm) 28π mm mrad HOR.	VER.	BEAM LOSS %
SEPTUM	21.1	27.2	+-19	+-14	0.0	+-22	+-16	0.0
D4Q5	23		+-22	+-11	0.0	+-25	+-13	2.0
IBV1	39.6	58.0	+-30	+-11	0.0	+-35	+-12	1.3
Q30	$R_{1,2}$=67,43		+-53	+32,-42	5.1	+-51	-38,+31	13.6
Q29	"		+-31	+51,-64	2.4	+-37	+55,-66	8.2
Q25	"		+-19	+66,-48	0.0	+-23	+75,-58	0.5
B7	+-34	+-36	+-42	+29,-25	8.0	+-50	+32,-29	21.6
B6	+-34	+-36	+-22	+47,-44	2.3	+-24	+54,-51	4.6
B5	+-72	+-23	+38,-43	+29,-30	2.3	+39,-45	+33,-35	4.8
B4	+-72	+-23	+-35	+33,-29	0.3	+-38	+38,-34	4.2
B3	+-34	+-36	+33,-29	+33,-30	2.3	+35,-30	+38,-34	4.8
B2	+-34	+-36	+21,-12	+47,-38	2.8	+24,-14	+53,-42	7.9
Q14	$R_{1,2}$=67,43		+27,-26	+65,-48	0.6	+31,-30	+76,-58	2.6

all other aperture limitations are excluded. The losses at the bending magnets (B2, B3, B4, B5, B6, and B7) were measured at the the upstream side.

2.2. Direct Tracing from the Ellipses at the Pulsed Dipole and at the Q7 Quadrupole

The SYNCH output was used to define the edges of ellipses with 20π and 28π mm mrad emittances at the entrance to the pulsed dipole and at the Q7 quadrupole.

Tables 2 and 3 present the positions with the corresponding losses of the 28π mm mrad beams when the starting limits were defined at the pulsed dipole and at the Q7 quadrupole. The emittances along the line when the beam was defined at the pulsed dipole were of the order of 50π mm mrad. When the limits of the beam were set up close to the Q7 quadrupole all emittances (both vertical and horizontal) measured close to 30π mm mrad.

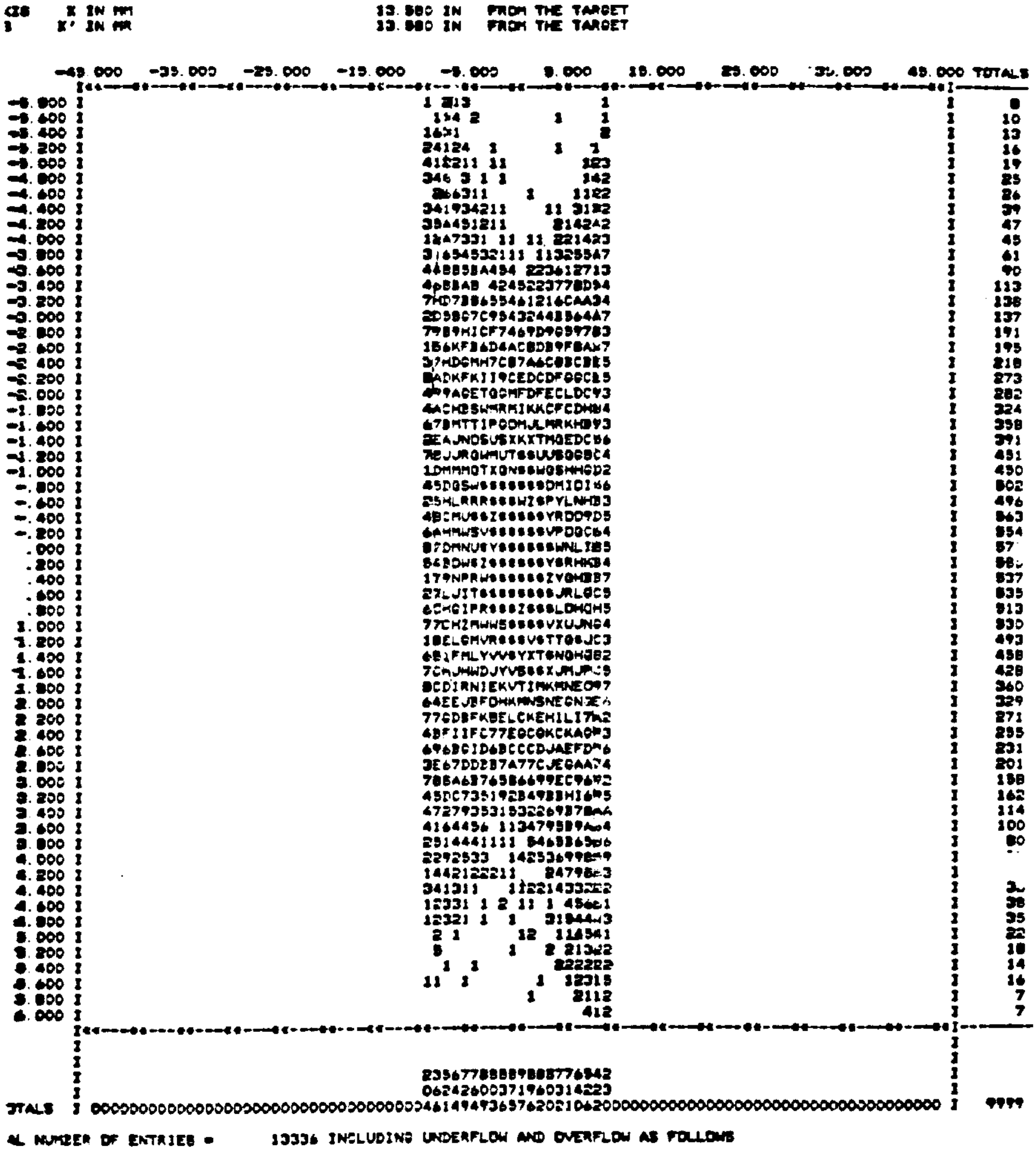
TABLE 2 TABLE 3

DIRECT TRACING FROM ELLIPSES AT THE PULSED DIPOLE AND AT THE Q7 QUADRUPOLE

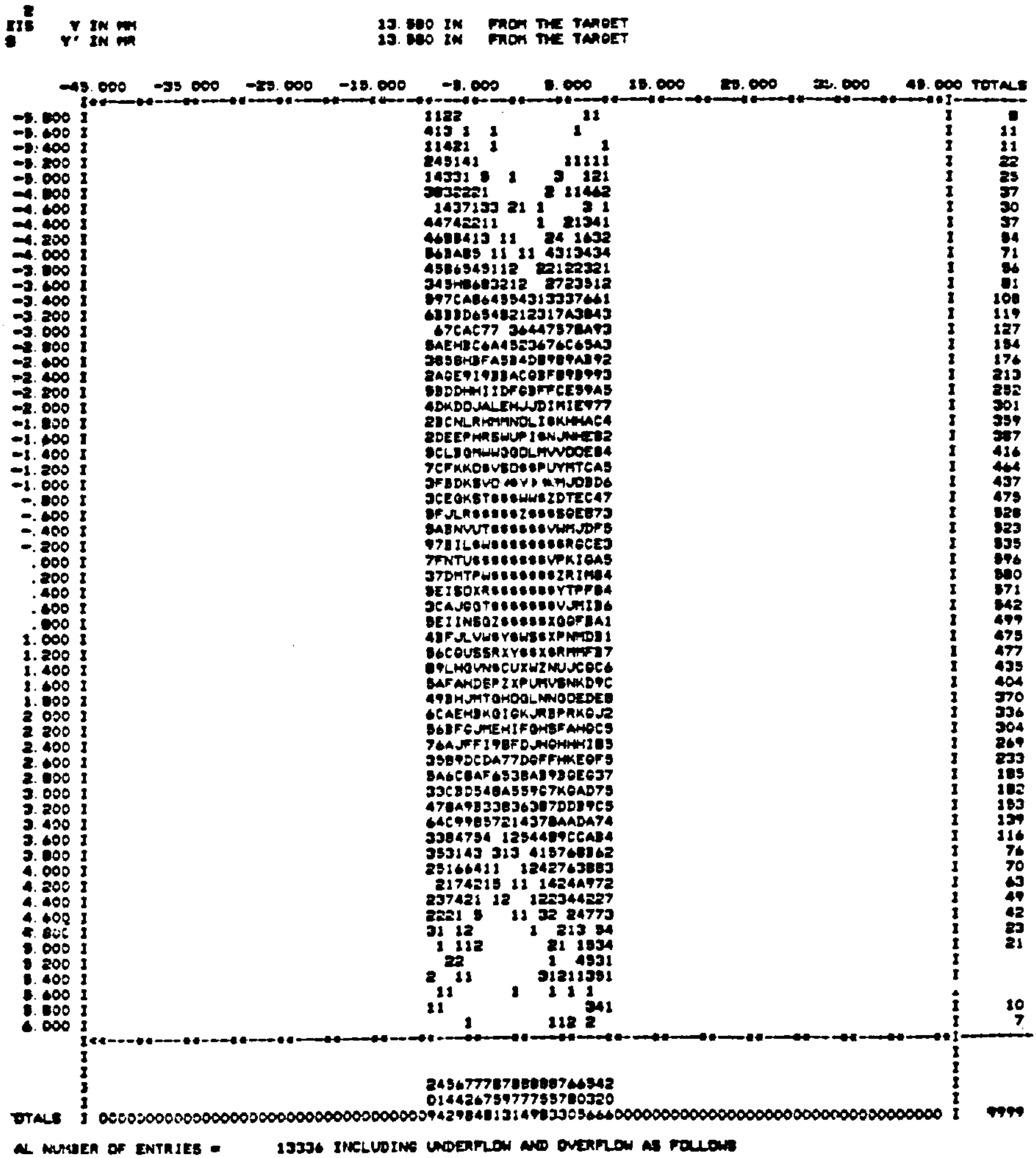
FROM THE PULSED DIPOLE $\epsilon_x \simeq 50\pi$ mm mrad $\epsilon_y \simeq 50\pi$ mm mrad		FROM THE Q7 QUADRUPOLE $\epsilon_x \simeq 30\pi$ mm mrad $\epsilon_y \simeq 30\pi$ mm mrad	
MAGNET	LOSS (%)	MAGNET	LOSS (%)
B2	4.0	B2	1.95
B3	6.1	B3	0.1
B6	3.3	B6	0.05
B7	15.9	B7	5.5

3. DIRECT TRACING FROM THE REAL DISTRIBUTION

With the TURTLE antiprotons were traced from the target through the AP-2 line with their real distribution without taking into account other particles created in the target. Fig. 1 and fig. 2 present the distributions of antiprotons at the end of the lithium lens in the x-x' and y-y' phase space obtained from the real distribution at the target. Since almost all created particles are lost at the lithium lens it is necessary to use a much higher number of rays (at least 100 000) to be able to obtain reasonable distributions along the AP2-line.


X IN MM
13.580 IN FROM THE TARGET
X' IN MR
13.580 IN FROM THE TARGET
TOTALS
AL NUMBER OF ENTRIES = 13336 INCLUDING UNDERFLOW AND OVERFLOW AS FOLLOWS

- Figure 1 -

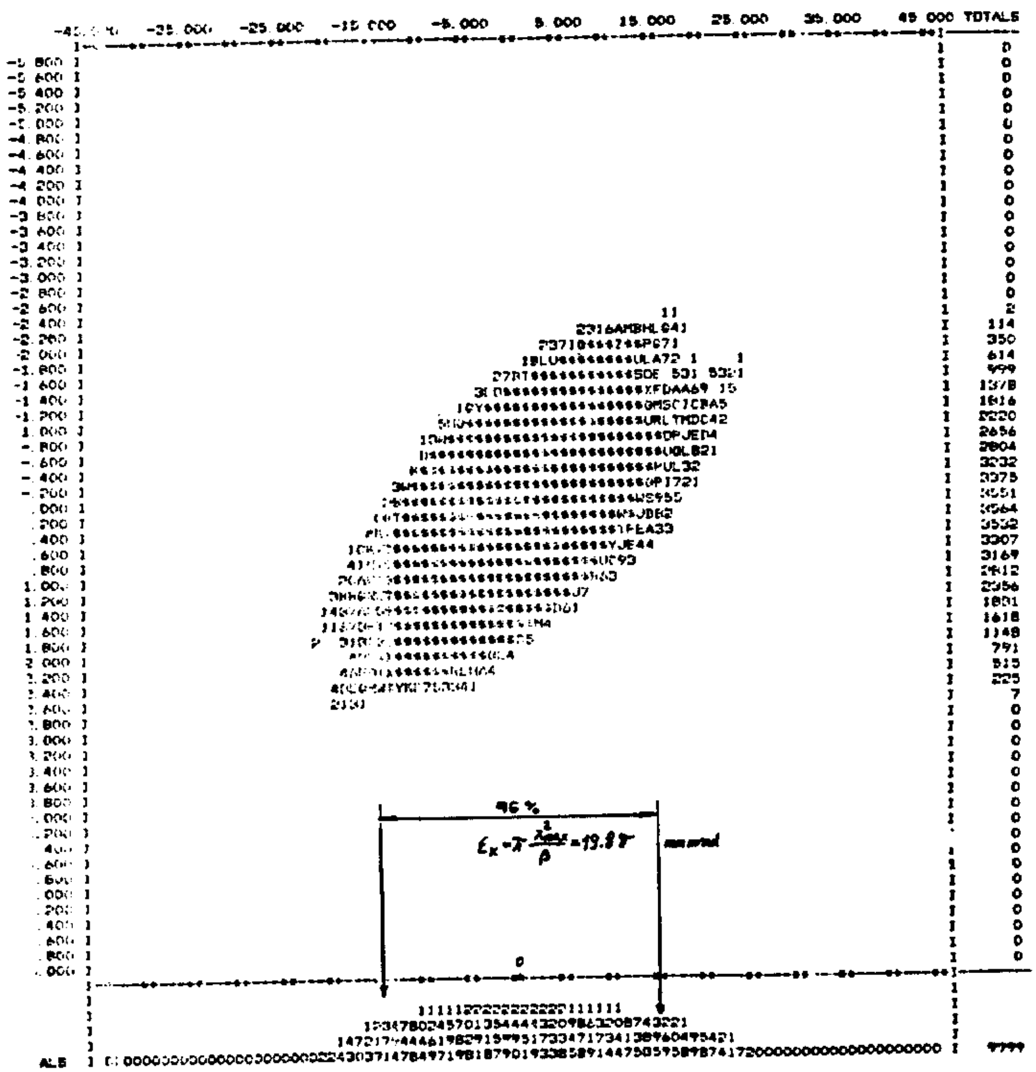

Y IN MM 13.580 IN FROM THE TARGET
Y' IN MR 13.580 IN FROM THE TARGET
TOTALS
AL NUMBER OF ENTRIES = 13336 INCLUDING UNDERFLOW AND OVERFLOW AS FOLLOWS

- Figure 2 -

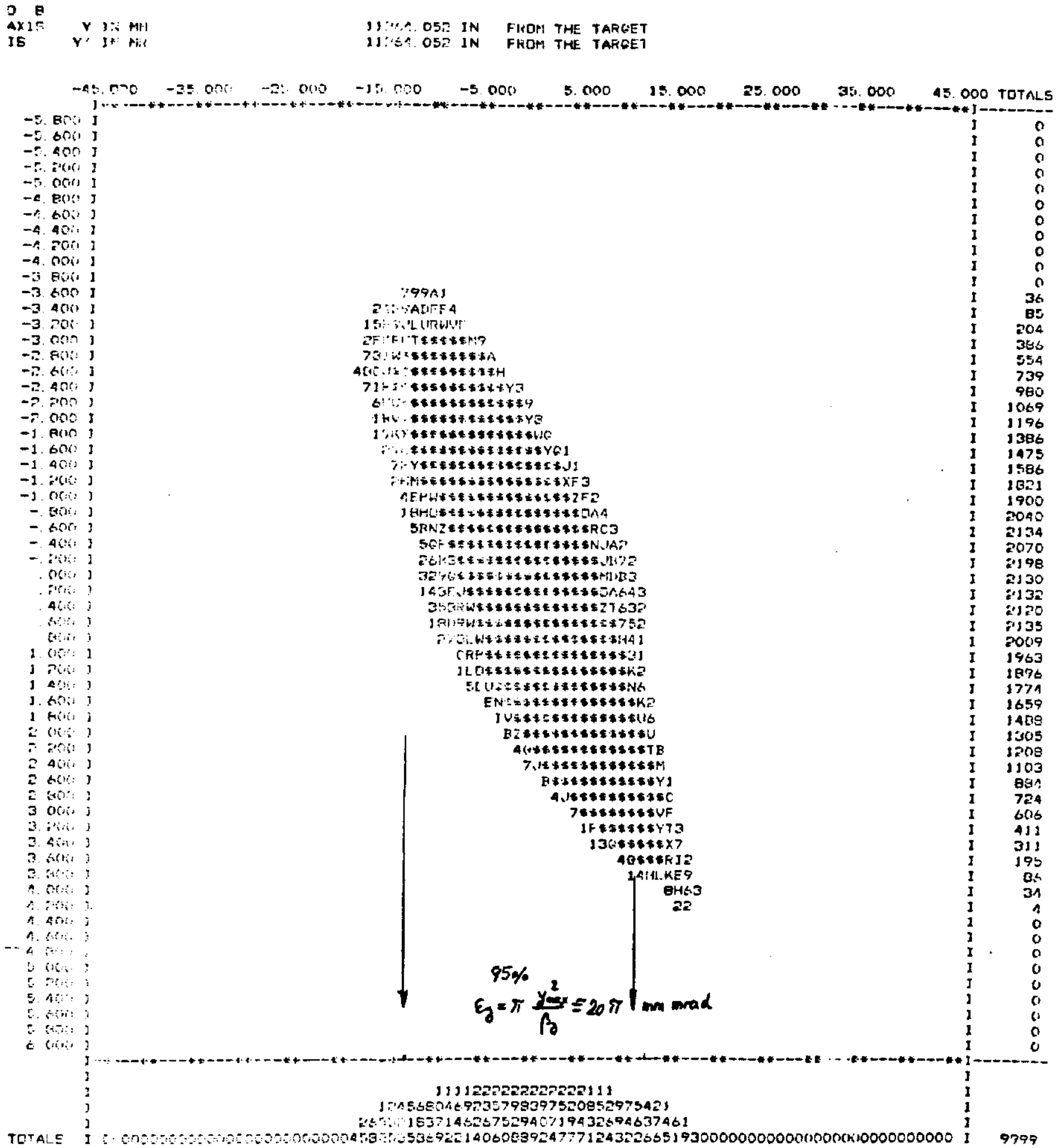
3.1 Present Acceptance of the AP-2 Line

When 400 000 rays - antiprotons were traced from the target only 45 000 of them reached the Debuncher. The distributions of antiprotons in the x-x' and y-y' phase space at the D4Q3 quadrupole in the Debuncher are presented in fig. 3 and fig. 4, respectively. The collimator slits were wide open. The estimated horizontal and vertical acceptances of the AP-2 line from the presented histograms are:

$$A_x \simeq 19.7\pi \ \text{mm mrad and} \quad A_y \simeq 20\pi \ \text{mm mrad}.$$



- Figure 3 -


FROM THE TARGET
FROM THE TARGET
-45.000
-35.000
-25.000
-15.000
-5.000
5.000
15.000
25.000
35.000
45.000
TOTALS
TOTALS
9799
95%
$\varepsilon_y = \pi \frac{y_{max}^2}{\beta_y} \cong 20\,\pi$ mm mrad

- Figure 4 -

The bends, acting as scrapers, again represented the highest loss points along the AP2-line. Percentage-wise the losses are much higher and distributed differently with respect to the results obtained from the reverse ray tracing since the incoming beam emittances are much higher. Table 4 presents the losses of a very high emittance beam at the bends without taking the lithium lens loss into account.

TABLE 4

DIRECT TRACING FROM THE REAL DISTRIBUTION
LOSSES AT THE BENDS

MAGNET	LOSS
B2	44%
B3	25.8%
B6	10.3%
B7	33.4%

The loss of antiprotons at a specific dipole was obtained when the aperture limitations of the other dipoles were removed.

3.2 Direct Tracing with the Closed Collimators

The antiproton horizontal and vertical beam emittances at the position of the first horizontal collimator both measured $\epsilon_x=\epsilon_y=$ 96.4π mm mrad. The lithium lens was set up to a field of 80 kG (the present operational condition). The 96.4π mm mrad emittances at the first collimator were obtained from the real distribution at the target with present aperture limitations from the target up to the collimator.

The beam size was lowered by closing two pairs of collimators to the distances determined by the reverse TURTLE runs. Four histograms were obtained in each reverse run at the collimators positions. For the reverse tracing the 20π and 28π mm mrad emittance beams were defined in the Debuncher.

The beam size in the direct tracing with the closed collimators was measured by the histograms along the line. The positions of the four slits were corrected in steps until emittances of the beam along the line reached the required values. The losses of the 28π mm mrad beam at the bends, when other dipole aperture limitations were removed, are presented in table 5.

It has to be noted that the lithium lens was still set up to 80 kG field although the lens will run with a higher field when the acceptance of the line and the Debuncher are raised to 28π mm mrad.

TABLE 5

DIRECT TRACING WITH THE CLOSED COLLIMATORS
LOSSES AND THE BEAM SIZES AT THE BENDS

MAGNET	LOSS (%)	BEAM POSITION	HORIZONTAL BEAM SIZE	VERTICAL BEAM SIZE
B2	0.13	UPSTREAM*	Δx={-36,+36}	Δy={-21,+21}
		DOWNSTREAM	Δx={-24,+24}	Δy={-36,+33}
B3	0.04	UPSTREAM	Δx={-22,+24}	Δy={-34,+36}
		DOWNSTREAM	Δx={-36,+36}	Δy={-24,+24}
B6	1.40	UPSTREAM	Δx={-34,+32}	Δy={-32,+36}
		DOWNSTREAM*	Δx={-26,+26}	Δy={-46,+48}
B7	7.85	UPSTREAM*	Δx={-30,+30}	Δy={-46,+48}
		DOWNSTREAM**	Δx={-52,+50}	Δy={-30,+30}
AVAILABLE APERTURE (mm)			Δx={-34,+34}	Δy={-36,+36}

Locations where the losses showed up are marked with "*".

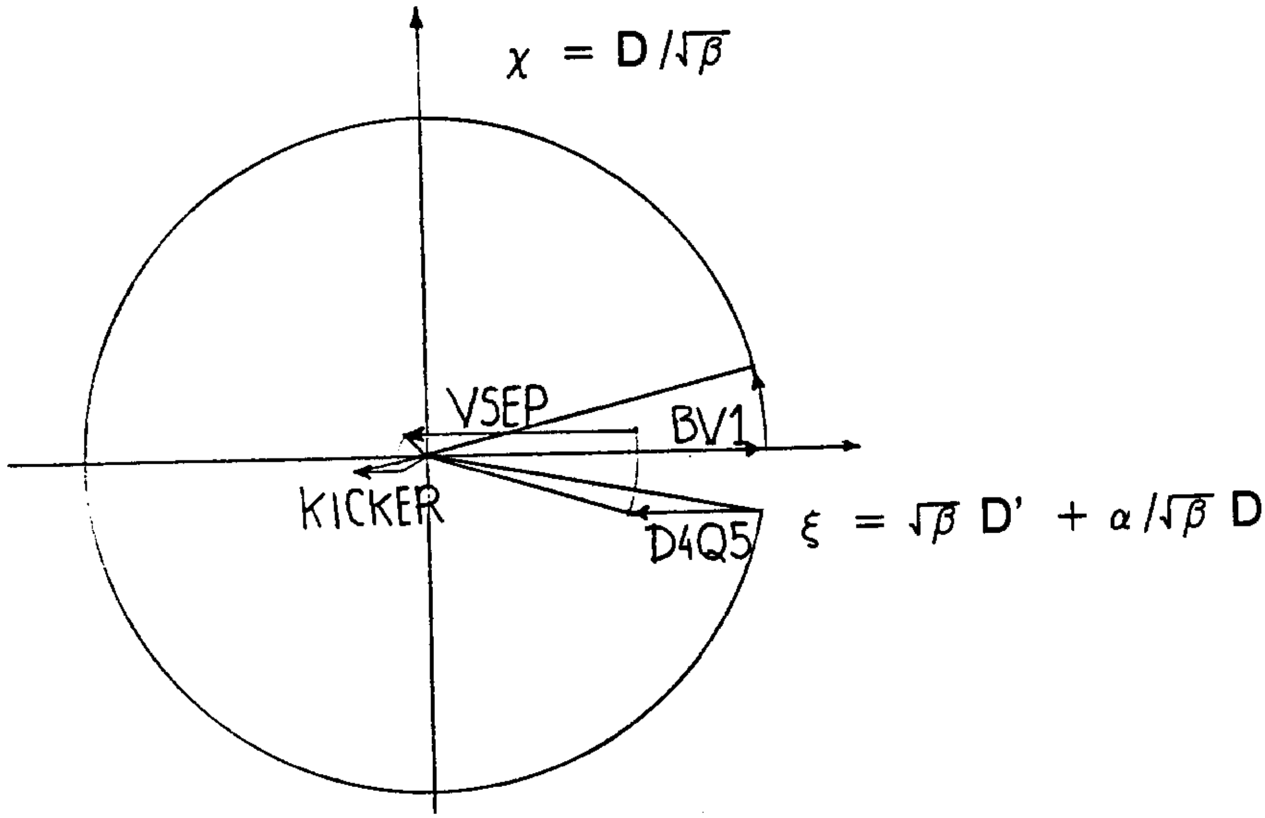
4. LATTICE FUNCTIONS

The existing settings of the quadrupoles used in the TURTLE were also used as an input for the SYNCH program to obtain the betatron functions and to check if the AP2-line matches the Debuncher. The SYNCH output showed no real difference with respect to the existing TRANSPORT output and the values of the betatron functions in the Debuncher were very close to the values given in the Debuncher design report.

The SYNCH output of the betatron functions, with the same quadrupole settings as used in the previous TURTLE calculations, is presented in TABLE 6.

The vertical dispersion match between the AP-2 line and the Debuncher was first examined by the thin element approximation(3). It is clear from figure 5 that the match is not perfect since the last vector downstream of the kicker does not point the origin of the new coordinate system, but the error is very small.

The SYNCH output in table 6 shows that values of the vertical dispersion in the Debuncher are very small.



- Figure 5 -

5. CONCLUSIONS FROM THE TRACE ANALYSES

To raise the admittance of the AP2-line from the existing 20π mm mrad up to 28π mm mrad it is necessary to open the aperture of the B2, B3, B6, and B7 bends both horizontally and vertically. Other losses along the line are much smaller.

The losses at the Q33 quadrupole were examined in detail due to their persistent occurrence. They occurred due to a smaller beam pipe size (with a radius of 26.9875 mm) which is located in the tunnel downstream of the Q33 quadrupole and is used to allow beam passage through the D4Q5 quadrupole. The beam in the AP-2 line is kicked upward by the D4Q5 quadrupole. The center of the small pipe is placed vertically above the D4Q5 quadrupole pipe used for the Debuncher circulating beam. When the losses of the traced rays at all other locations along the AP-2 line were removed the loss at the Q33 quadrupole occured only when the pipe was placed within the quadrupole. When the location of the small pipe was defined in the program downstream of the Q33 quadrupole the losses at the Q33 as well as at the small pipe were very small.

The Q29 and Q30 quadrupoles have shown noticable losses when the rays were traced from the Debuncher backward to the target but they were much smaller in the normal direction from the target to the Debuncher when the real distribution at the target was used.

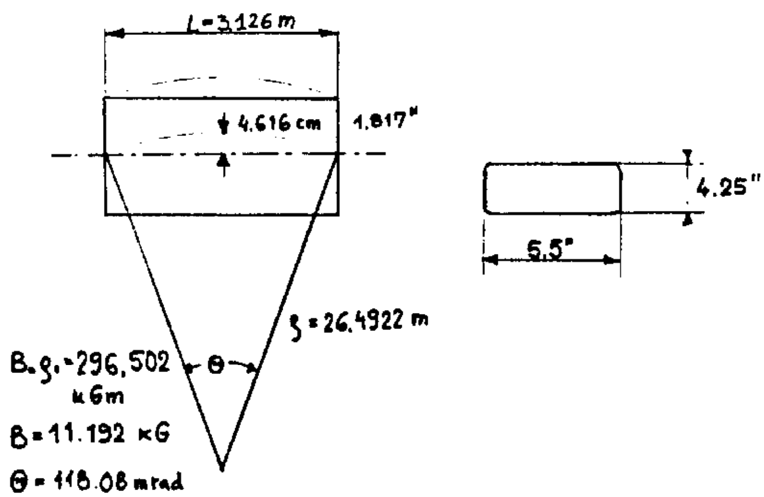
The first and the second quadrupole downstream of the lithium lens (Q1 and Q2) showed losses of the order of 10% when the particles were traced from the real distribution. When the 28π mm mrad emittance beam was created at the end of the lithium lens and traced along the AP-2 line these losses were negligible. The tracing was not entirely precise because the distances between the lithium lens and the pulsed dipole as well as the settings of the Q1, Q2, Q3, Q4, Q5 ,Q6, and Q7 quadrupoles will change.

The B2, B3, B6, and B7 magnets were built flat. To correct the horizontal aperture limitation due to a sagitta of these flat magnets it is necessary to curve their steel and put a new beam pipe which conforms to the new curved magnet shape. The vertical aperture restriction can be corrected with spacers made of magnetic steel.

6. PROPOSAL FOR IMPROVEMENT OF THE AP-2 LINE APERTURE

There are a total of six bends in the AP-2 line. They will represent an aperture limitation for the next collider run if the acceptance of the Debuncher is raised to 28π mm mrad. For the next collider run the acceptance of the line has to be raised from 20π mm mrad up to 28π mm mrad. The first two and the last two magnets in a row are of the same kind (6-3-120) while the third and the fourth magnets are the TEV-1 small dipoles.

Four of these bends (the B2, B3, B6, and B7) are magnets 123.08" long (6-3-120) and they were built flat because they are used in the transfer lines. Presently the beam pipes in these magnets are straight with a 3.25" vertical gap (external dimensions).



- Figure 6 -

The geometrical aperture of these magnets limits the acceptance of the AP-2 line both horizontally and vertically. The 6-3-120 magnets bend the beam by an angle of 118.077 mrad (6.765°). The sagitta is 4.616 cm (1.817"), as shown in figure 6. To open the horizontal aperture these magnets have to be curved to eliminate the 1.817" sagitta with a new beam pipe which conforms to the new curved shape. The vertical aperture has to be opened by 1 inch, so the gap should be widened by putting a one inch spacer plate between the two cores. The spacers have to be made of magnetic steel (for example cold rolled 10-18) and they have to match the two bent cores. The new beam pipe cross section is presented in fig. 6. The vertical outside dimension of the pipe should measure 4.25".

The two central small TEV-1 dipoles are used to bend the beam by an angle of 83.93 mrad. Their cores as well as the beam pipe were designed to match a bending angle of 95.20 mrad; horizontally they do not present an aperture limitation. The vertical aperture limitation will be eliminated by opening the gaps by 0.754". The 0.754" inches thick plate made of magnetic steel (cold rolled 10-18) is needed as a vertical spacer. The new beam pipes in the TEV-1 small dipoles should match the 83.93 mrad angle of the cores and should be 3/4 inches wider with respect to the previous pipes.

REFERENCES:

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(2) A.A. Garren, A.S. Kenney, E.D. Courant, and M.J. Syphers, "A User Guide to SYNCH", Internal Fermilab Publication FN-420, June 1985.

(3) D. Trbojevic and R. Gerig, "DESIGN AND COMMISSIONING OF THE DO VERTICAL NONDISPERSIVE OVERPASS IN THE FERMILAB MAIN RING", Presented at the "1989 IEEE PARTICLE ACCELERATOR CONFERENCE" in Chicago, March 1989.